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Colloidal Stability of Gold Nanoparticles Coated with Multithiol-Poly(ethylene glycol) Ligands: Importance of Structural Constraints of the Sulfur Anchoring Groups

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Abstract

Gold nanoparticles (AuNPs) coated with a series of poly(ethylene glycol) (PEG) ligands appended with four different sulfur-based terminal anchoring groups (monothiol, flexible dithiol, constrained dithiol, disulfide) were prepared to explore how the structures of the sulfur-based anchoring groups affect the colloidal stability in aqueous media. The PEG-coated AuNPs were prepared by ligand exchange of citrate-stabilized AuNPs with each ligand. The colloidal stability of the AuNPs in different harsh environmental conditions was monitored visually and spectroscopically. The AuNPs coated with dithiol- or disulfide-PEG exhibited improved stability under high salt concentration and against ligand replacement competition with dithiothreitol compared with those coated with their monothiol counterpart. Importantly, the ligands with structurally constrained dithiol or disulfide showed better colloidal stability and higher sulfur coverage on the Au surface compared to the ligands with more flexible dithiol and monothiol. X-ray photoelectron spectroscopy also revealed that the disulfide-PEG ligand had the highest Au-S ratio on the Au surface among the ligands studied. This result was supported by energy minimization modeling studies: the structurally more constrained disulfide ligand has the shortest S-S distance, and could pack more densely on the Au surface. The experimental results indicate that the colloidal stability of the AuNPs is systematically enhanced in the following order: monothiol < flexible dithiol < constrained dithiol < disulfide. The present study indicates that the colloidal stability of thiolated ligand-functionalized AuNPs can be enhanced by (i) a multidentate chelating effect and (ii) use of the constrained and compact structure of the multidentate anchoring groups.

Keywords: Disulfide, Bidentate, Monothiol, Constrained dithiol, DTT

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1. Introduction

The application of colloidal inorganic nanoparticles (NPs) in biology has grown tremendously in the past decade, and this has been driven primarily by the ever increasing range of their utility.¹⁻¹³ As perhaps the most common NP material, gold NPs (AuNPs) are now found in various biologically-related roles including signal transducers in colorimetric assays and diagnostics, energy transfer quenchers, cellular labels, multi-photon imaging, single molecule tracking and delivery vehicles along with platforms for photothermal therapy.^{1, 2, 6-8, 14-18} For effective performance within most biological applications, colloidal AuNPs are required to be biocompatible and highly stable in biological environments. More specifically, they need to fulfill the following expectations: (1) high solubility in aqueous environments; (2) resistance towards ionic molecules (e.g., NaCl, NaOH, HCl) found in biological buffers; (3) resistance to reducing agents such as dithiothreitol (DTT), tris(2-carboxyethyl)phosphine (TCEP), mercaptoethanol, glutathione and cysteine; and (4) low nonspecific binding to the abundant biomolecules in biological serum (e.g., proteins, peptides, nucleic acids); (5) resistance to heat treatments (e.g., >80 °C for DNA hybridization).^{6-8, 16, 17, 19} As AuNPs are not colloiddally stable in solvent or aqueous environments without surfactants, almost all AuNPs are stabilized or modified with surface ligands or other functionally-related (bio)molecules which promote their dispersion, prevent aggregation and sometimes provide additional chemical groups or ‘handles’ for further bioconjugation.^{1, 3, 5-7} Thus, the colloidal stability of AuNPs is directly affected by the physical and chemical properties of the ligands, and the design of ligands is critically important to the overall experimental results in biological applications.

Most surface ligands are modular in nature and typically consist of an anchoring group for attachment to the AuNP surface, a backbone or spacing group, and a terminal functional group(s); the latter often display different chemical groups to impart various properties to the AuNP such as charge and a reactive site.^{2, 3, 16, 20} Interaction between anchoring groups and the AuNP surface can be driven by different types of mechanisms such as metal-ligand coordination (S-Au bonding, carboxyl-Au interaction, histidine-Au coordination), electrostatic attraction (positively charged peptide/protein/polymer - negatively charged AuNP) and hydrophobic adsorption (hydrophobic protein pockets - AuNP).^{1, 20} Each mechanism will also be characterized by different affinities and avidities. The chain length and hydrophobicity of the ligand backbone can also affect the

quality of the ligand layer surrounding the AuNPs as well as the overall solubility. For example, an alkyl chain backbone contrasts well with a poly(ethylene glycol) (PEG) backbone in this matter. The nature of the terminal functional groups can be modified to control repulsive or attractive forces between the AuNPs and other molecules for nonfouling or electrostatic conjugation properties, respectively. Alternatively, the termini can be designed to display groups for specific conjugation chemistries such as carbodiimide coupling (amine-carboxyl group), click chemistry (alkyne-azide) and biomolecular interaction (biotin-avidin, glycan/carbohydrates-lectins).^{3, 16}

A wide variety of surface ligands have been developed to modify the surface and improve the colloidal characteristics of AuNPs.^{1, 19, 21-45} Citric acid has been the most commonly used ligand when negatively charged surfaces or a rather loose ligand shell is required for further modification.²¹ Phosphine or phosphine oxide derivatives were used for preparation of smaller sized AuNPs (1.5 nm diameter).²² Cetyltrimethylammonium bromide (CTAB) has been frequently used as a cationic surfactant.²³ Amine-stabilized AuNPs have also been prepared using octadecylamine / tri-*n*-octylphosphine oxide (TOPO),²⁴ oleylamine²⁵ and L-lysine.²⁶ Pyridine and similar molecules have also been applied for modification of AuNPs.²⁷ AuNP colloidal stability has been significantly improved by preparing a relatively thicker shell with polymers or polyelectrolytes such as poly(N-vinyl-2-pyrrolidone) (PVP),²⁹ polyethylenimine (PEI),³⁰ thioether-terminated polymers,³¹ poly(*p*-phenyleneethynylene),³² silica,³³ and multidentate polymers.³⁴ Since Brust's report of a synthetic method using dodecanethiol to make strong coordinating bonds with Au, thiol-based ligands have now become one of the most popular ligands for stabilizing AuNPs due to the strong Au-S binding.³⁵ Colloidal stability of AuNPs for biological applications has been demonstrated by a variety of thiol-based ligands such as mercaptopropionic acid,³⁶ glutathione,³⁷ thiol-terminated poly(ethylene glycol) (PEG-SH),^{19, 38,39} dithiocarbamate,²⁸ a multidentate-PEG,^{40-42, 46, 47} a multidentate-zwitterionic ligand,⁴⁷ thiol-terminated DNA,⁴³ cysteine-containing peptides⁴⁴ and bovine serum albumin (BSA).⁴⁵ On the other hand, the structural changes of thiol anchoring groups have been tried to enhance the stability of AuNPs. Shulz et al studied the effect of the spacer structure on the stability of AuNPs with PEG-SH.¹⁹ Mirkin et al. studied the importance of multidentate structures of thiol anchoring groups attached to DNA to enhance the stability of DNA-coated AuNPs.⁴³ To the contrary, Hou et al. reported that the cyanide etching and oxidation rates of dithiolate-stabilized

small AuNPs (1-3 nm) was faster than those of the dodecanethiolate- or mixed ligand-stabilized AuNPs.⁴⁸ Our group demonstrated that the coordination number of the ligands attached to the AuNPs played an important role in colloidal stability. Dithiol-PEG ligand has been shown to enhance the stability of AuNPs and quantum dots (QDs) compared to monothiol-PEG ligands.⁴¹⁴⁹ Dithiol-PEG-stabilized AuNPs showed long-term stability across a wide range of pHs (pH 2-13) and in high salt concentration (2M NaCl) due to the high water solubility of PEG and the strong binding of dithiol to the NP surfaces. We have also found that small AuNPs with high curvature are more sensitive to cyanide etching and need ligands capable of a high surface packing density to improve the colloidal stability.^{41, 49} The previous study indicated that balance between the coordination number and surface packing density of the ligands is crucial to enhance the colloidal stability of AuNPs.

In the present study, we investigated how the structural differences of sulfur-based bidentate anchoring groups affect the colloidal stability of AuNPs. The focus of this study is on the spacing between the sulfur anchoring groups in the ligand, structural constraints and flexibility of the anchoring groups as well as the distance between the backbone and the sulfur anchoring group. For this, we designed four different ligands with different sulfur-based anchoring groups, and prepared AuNPs coated with those ligands (AuNP-PEGs). While each ligand (MP7M, BP7M, DP7M and TP7M) has an identical PEG backbone (averaged molecular weight ~ 750 Da) and a methoxy terminal group, each of them has a different sulfur-based anchoring group, see Figure 1a. MP7M has a monothiol originated from mercaptohexanoic acid. BP7M has a dithiol anchoring group with a relatively flexible structure and spacing between the two thiol units. DP7M has a dithiol anchoring group originated from dihydrolipoic acid (DHLA). TP7M has a disulfide anchoring group from thioctic acid (TA, closed-ring form of DHLA). MP7M has one thiol for each PEG chain, and the others have two thiols (or one disulfide) for each PEG chain. The influence of the different anchoring group on the colloidal stability of the aqueous phase AuNP-PEGs was explored side by side under the following conditions: (a) high salt concentrations (2M NaCl), (b) in the presence of dithiothreitol (DTT), which has strong binding affinity with Au surfaces and could replace the original ligands, and (c) at high temperature. Our present study demonstrated that the bidentate ligands (dithiol and disulfide) and in particular, the structurally constrained disulfide anchoring group enhanced the NPs' tolerance to high ionic

buffer conditions, high temperatures, and competition against the other strong Au binding reagents.

The degree of thiol coverage on the Au surface for each ligand was studied using X-ray photoelectron spectroscopy (XPS). The following relationships were established: (i) the sulfur-based bidentate PEGs exhibited a higher Au-S binding ratio (higher S coverage) than the monothiol-PEG; (ii) AuNPs assembled with the bidentate ligands were more colloidally stable than the monothiol-PEG AuNPs, despite the smaller number of PEG units per thiol (one PEG ligand per bidentate thiol ligand (1 PEG, 2 S), compared to one PEG ligand per monothiol ligand (1 PEG, 1 S) (iii) the more structurally constrained the two sulfur atoms (the bidentate ligands) were, the higher S coverage on the surface of Au. We also estimated the distances between two sulfur atoms in the bidentate-PEGs based on energy minimization, and compared the stable anchoring positions of two adjacent sulfurs of each ligand on the Au surface. This modeling suggests that a match between the sulfur atom separation within the ligand and the distance of adjacent Au atoms on the AuNP surface is critical for a good thiol coverage on the NP surface and overall colloidal stability.

2. Experimental Section

2.1. Synthesis of ligands: MP7M, DP7M, TP7M, BP7M

All of the PEG ligands studied here were synthesized from methoxy-terminated PEG (MeO-PEG750-NH₂) with an average molecular weight of ~750 (ethylene oxide repeat units $n \sim 15$). Methoxy-terminated PEG-modified monothiol ligand (MP7M), PEG-modified thioctic acid ligand (TP7M) or PEG-modified dihydrolipoic acid ligand (DP7M) were synthesized, and characterized following the procedures detailed in the references.^{41, 50} See Figure 1 for the relevant structures of ligands. PEG-modified dithiol ligand with relatively flexible structure (BP7M) was synthesized by procedures detailed in the Supporting Information.

2.2. Preparation of AuNPs

We prepared AuNP-PEG using 15 nm sized citrate-stabilized AuNPs (Ted Pella, Inc.) by ligand exchange method.⁴⁰ Each ligand was added to the citrate-stabilized AuNP dispersion in water at pH 8-8.5 (adjusted from deionized water using NaOH) and stirred for 8 hours. 10 ml of AuNPs stock solution (2.3 nM) was mixed with 26 μ mol of the bidentate ligand (BP7M, DP7M, or TP7M) or 51 μ mol of the monodentate ligand (MP7M). The total ratio of thiol-to-Au surface atoms in the reaction mixture was $\sim$ 200. After stirring the reaction mixture at room temperature overnight, free ligands were removed by three cycles of concentration/dilution using a membrane filtration device (Millipore, 100 KDa molecular weight cut-off). Deionized water was used for purifying the AuNP dispersion. Each AuNP dispersion displaying the different ligands was then concentrated up to 4 - 5 times ($\sim$ 10 - 11 nM) in water and stored at 4 °C until use.

2.3. XPS analysis

Self-assembled monolayers (SAMs) of each ligand were deposited by dipping flame-annealed Au substrates into the dipping solution. Flame annealing produces Au films with predominantly (111) surfaces.⁵¹ The concentration of the dipping solution containing each ligand was fixed to 130 mM for the bidentate ligands (BP7M, DP7M, TP7M) and 260 mM for the monodentate ligands (MP7M and mercaptoundecanoic acid (MUA)) in water. MUA-SAM was used as control. A cleaned, flame-annealed Au substrate was immersed into each solution overnight and washed with methanol and water three times. The Au-SAM surface was dried and kept under N₂ for further use. XPS analysis was performed using a Thermo Scientific K-Alpha XPS instrumentation with a monochromatic Al K-Alpha source, and the spectral peaks of core levels were fitted using commercial XPS analysis software. The fitted functional form was a single Voigt doublet superimposed on a Shirley-type (Au) or polynomial (S) background function.⁵²

2.4. Molecular modeling of ligands and ligand-gold interactions

All models were created using tools in UCSF Chimera (version 1.4.1). Energy minimization was carried out in Chimera using the built-in features including ANTECHAMBER (version 1.27) and the AM1-BCC method of calculating charges.⁵³ The gold surface was created using the cubic form of gold with $a = b = c = 4.0786$ Å and the Fm3m space group. Based on Au-S interactions found in the Cambridge Structural Database (CSD) (www.ccdc.cam.ac.uk/products/csd/), the Au-S bond distance was set to be 2.3 Å when docking ligands onto the Au surface.

3. Results and Discussion

3.1. Synthesis of ligands and AuNPs

Four sulfur-based ligands were synthesized from MeO-PEG750-NH₂⁵⁰ by amide bond formation with different sulfur anchoring groups (Figure 1a): (1) monothiol-PEG (MP7M) with mercaptohexanoic acid,⁴¹ (2) dithiol-PEG (BP7M) with cystamine derivatives (Figure S1, Supporting Information), (3) dithiol-PEG (DP7M) with dihydrolipoic acid (DHLA), (4) disulfide-PEG (TP7M) with thiocetic acid (TA).⁵⁰ Each synthesized ligand has the same methoxy-terminated PEG with different structures within the sulfur-based anchoring groups. This allows us to examine how the structural differences of the sulfur-based anchoring groups affect the colloidal stability of AuNPs. The AuNPs coated with each ligand (AuNP-PEGs: AuNP-MP7M, AuNP-BP7M, AuNP-DP7M, AuNP-TP7M) were prepared by ligand exchange from commercial citrate-stabilized AuNPs (Ted Pella, Inc., diameter ~15 nm).⁴¹ We used excess amounts of the ligands (ratio of thiol-to-Au surface atom ~ 200) in slightly basic pH (8-8.5); this condition enhances the Au-S interaction and helps the ligands effectively replace the original citrate ligands of AuNPs. Previously we confirmed the effectiveness of our ligand exchange protocol by comparing the FT-IR spectra collected from TP7M-modified AuNPs and free ligand (TP7M), compared to citrate AuNPs. The amide bonding (C=O stretch at ~1670 cm⁻¹/ N-H bending at ~1540 cm⁻¹) and CH₂ vibrational mode (~2850, ~2920 cm⁻¹) of AuNP-TP7M matched well those of TP7M, and there was no distinguishable contribution from citrates (original large C=O stretch band at ~1590 cm⁻¹ of citrate is gone).⁴⁹ The absorption spectra of AuNP-PEGs showed no significant change from that of the original citrate-stabilized AuNPs (AuNP-Citrate) (Figure 1b); there was neither apparent shift of the surface plasmon resonance band (SPB) at 520 nm nor absorbance changes over a wide wavelength range. While the hydrodynamic size in intensity mode measured by dynamic light scattering slightly increased after ligand exchange due to the length of PEG, the data showed no apparent sign of aggregation (Figure 1c and Table S1 in supporting information). The main peak was observed around 23~24 nm in the intensity profile of DLS, indicating no aggregation after ligand exchange over time except AuNP-MP7M showing very small tail. This result indicates that AuNP-PEGs have no microscopic aggregations

and surface etching after ligand exchange. The TEM images also showed no specific aggregation or size change in all the AuNP-PEGs samples after ligand exchange (data not shown).⁴⁹ Thus, PEG modification of AuNP surfaces was successfully carried out, and the sample preparation process was consistent for all the ligands.

3.2. Colloidal stability tests: high ionic solution, reducing reagent and aggregation factor

Using as-prepared AuNP-PEGs with different ligands, we examined the long-term colloidal stability under harsh environmental conditions. First, we tested the resistance of AuNP-PEGs in a high ionic buffer (2 M NaCl in water). Ionic buffers or salt solutions are commonly used in biological studies and frequently cause NP aggregation due to (i) screening repulsive forces between NPs originating from the surface ligands and (ii) decreased solubility of the ligands.⁵⁴ Since most of the AuNP-PEGs studied here were found to be very stable even in high salt concentration at room temperature,⁴¹ we sped up the aging process of AuNP-PEGs by heating the dispersion at 100 °C in 2M NaCl solutions. Because of no colloidal color differences between four AuNP-PEGs samples (with different ligands) and the same absorption spectra before adding NaCl (Figure 1b), we chose freshly prepared AuNP-TP7M as the control sample (marked as Cont. in the first column of Figure 2). After 5 minutes of heating, AuNP-MP7M dramatically changed to grey due to fast aggregation, and AuNP-BP7M turned purple (Figure 2a). The color of the AuNP-DP7M changed to light pink in 5 minutes and almost transparent in 15 minutes, presumably due to aggregation or adsorption onto the vial surface. However, the AuNP-TP7M colloidal solution turned to a darker purple color than three other samples after 15 minutes of heating in 2M NaCl, which indicated slower or less aggregation. To monitor microscopic changes of AuNP-PEGs under this high ionic condition, we also measured the absorption spectra (Figure 3). The absorption spectra of AuNP-MP7M and AuNP-BP7M became broader and the peak position of surface plasmon resonance band (SPB) was shifted bathochromically, which reflects the aggregation of AuNPs. The absorbance of the AuNP-DP7M solution decreased significantly while the AuNP-TP7M solution showed a relatively smaller decrease. For quantitative comparison of microscopic changes of AuNP-PEGs, we defined the accumulated flocculation (*AF*) as the increase of accumulated absorbance from 600 nm to 900 nm per absorbance at 520 nm (the peak of the original SPB):

$$AF = I/A - I_0/A_0 \quad (1)$$

where I_0 and I are total area from 600 to 900 nm in the absorption spectra of AuNP-PEGs before and after 15 minutes of heating in 2M NaCl, respectively (Figure 5a). A_0 and A are the absorbance at 520 nm before and after 15 minutes of heating in 2M NaCl, respectively. The higher AF value simply reflects the higher degree of aggregation. Monothiol-modified AuNP (AuNP-MP7M) showed the most accumulated flocculation after heating ($AF = 191$), and dithiol-modified AuNPs (AuNP-BP7M and AuNP-DP7M) showed less aggregation ($AF = 60 \sim 63$), which is $\sim 30\%$ of AuNP-MP7M (Figure 5b). Disulfide-modified AuNP (AuNP-TP7M) showed the least aggregation ($AF = 36$) which is $\sim 20\%$ of monothiol-modified AuNP and $\sim 60\%$ of the dithiol-modified AuNPs. This result indicates that the NP aggregation in high salt buffer is sensitive to the number of anchoring groups as well as their structures, and the close geometry of two sulfur atoms of the anchoring groups may be beneficial to effectively prevent NP aggregation.

Next, we examined the resistance of AuNP-PEGs in the presence of the strong reducing agent, dithiothreitol (DTT). DTT is commonly used to reduce disulfide bonds in a variety of biomolecules including peptides, proteins, antibodies, and thiol-modified DNAs.¹⁶ At high concentration, DTT can effectively displace the original ligands on the NP surface and bind to the AuNP surface because of its dithiol group and compact structure, which eventually leads to NP aggregation.^{40, 41, 55, 56} Therefore, strong resistance in the presence of DTT is particularly promising for applying AuNPs within biological assays, which are often carried out in media containing small thiol molecules such as cysteine, glutathione, mercaptoethanol, and DTT. We monitored the spectral changes of AuNP-PEGs in the presence of 1.5 M DTT, 0.8 M NaCl and 10 mM NaOH; basic pH buffer makes DTT more reactive. The DTT concentration used here is much higher than those measured for thiol-containing molecules in biological environments; for example, intracellular glutathione level is estimated to be 1 $\sim$ 10 mM.⁵⁷ While the monothiol-modified AuNP (AuNP-MP7M) immediately showed precipitation and completely lost the original red colloidal color in less than 20 minutes, while the other dithiol-modified AuNPs (AuNP-BP7M and AuNP-DP7M) were relatively stable for 20 minutes and the disulfide-modified AuNP (AuNP-TP7M) showed very little change even after 90 minutes (Figure 2b). The time variation of the absorption spectra of AuNP-PEGs showed microscopic changes of

each sample from 0 to 20 minutes after adding DTT solution (Figure 4). Overall, the spectral changes were similar to those of the NaCl test. The peak of SPB was bathochromically shifted due to aggregation of AuNPs and formation of their large clusters. The intensity of SPB also decreased due to precipitation of AuNPs. The absorption spectra of AuNP-MP7M changed faster than those of the other three AuNP-PEGs. The corresponding progression of accumulated flocculation, *AF*, with time was plotted in Figure 5c. AuNP-MP7M showed the most significant aggregation and the *AF* steeply increased in the first 10 minutes and was gradually saturated (*AF* ~120). AuNP-BP7M and AuNP-DP7M had relatively smaller *AF* values (40 ~ 50) than AuNP-MP7M, and AuNP-TP7M showed the smallest *AF* values (~30) which is ~25% of monothiol-modified AuNP and ~60% of the dithiol-modified AuNPs. This trend of *AF* differences in DTT test was very similar to that noted in the previous NaCl test. The SPB shifts also dramatically increased with time (Figure 5d). The monothiol ligand (AuNP-MP7M) and relatively flexible dithiol ligand (AuNP-BP7M) resulted in large bathochromic SPB shifts (130 ~ 160 nm in 20 minutes), indicating NP aggregation. On the other hand, the structurally constrained dithiol (AuNP-DP7M) and disulfide (AuNP-TP7M) ligands led to a smaller SPB shift (60 ~ 70 nm in 20 minutes) and slower aggregation of AuNPs. These side-by-side comparisons observed for mono-, dithiol- and disulfide-modified AuNPs suggest that the dominant factor for stabilizing AuNPs against surface invasion by small thiolated molecules (DTT) is not only the multidentate nature of the anchoring groups but also the structural constraint at the anchoring units (in DP7M and TP7M), which modulate the overall ligand binding strength onto the metal surface. Enhanced stability of metal (Au, Ag) NPs using thioctic acid modified oligonucleotides in the presence of 10 mM DTT has been previously reported.⁵⁶

3.3. Surface coverage of ligands: XPS analysis

For further investigation of the binding properties affected by the different ligand structures, X-ray photoelectron spectroscopy (XPS) was used to analyze bonding of the sulfur-based anchoring groups onto the Au surface. SAMs of the ligands were prepared on the Au surface by dipping the Au substrates into each ligand solution. Core level shifts in the XPS spectra are indicative of the chemical state of the emitting atom, and intensities of the emitted photoelectrons can be used for quantitative analysis of the chemical compositions. Additionally, the intensities of photoelectrons of the monolayers coated by four different PEG ligands can be used to estimate

the relative surface coverage of the adsorbed species. In the plot of intensity vs. binding energy (158 ~ 168 eV) (Figure 6a), only S 2p doublets (S 2p_{3/2,1/2}) were observed around 162.1 and 163.2 eV for the monothiol-modified Au surface (Au-MP7M) and the disulfide-modified Au surface (Au-TP7M). This result indicates that only the bound sulfur species are present on the Au surface, and a single layer of sulfur atoms is formed at the Au-S interface as expected for a well-formed SAM. In the case of dithiol-modified Au surface (Au-DP7M, Au-BP7M), there were small intensity contributions from unbound species of S 2p_{3/2,1/2} around 163.4 and 164.6 eV, overlapping partially in energy with the bound species and giving rise to triple peak feature in the raw data. The surface coverage of S atoms was calculated using S 2p (bound) and Au 4f (substrate) intensities. Because Au 4f, and S 2p photoelectron intensities are nearly identically attenuated by the hydrocarbon overlayer (due to their similar kinetic energies), a simple ratio of S/Au photoelectron intensities can be used to obtain the absolute sulfur coverage (n_s):^{58, 59}

$$n_s = \left(\frac{I_S}{I_{Au}} \frac{\sigma_{Au}}{\sigma_S} \right) \left(\frac{T_{Au}}{T_S} L_{Au}^0 N_{Au} \right) \quad (2)$$

where I_S and I_{Au} are the measured photoelectron intensities, and σ_S and σ_{Au} are photoelectron cross sections for the S 2p and Au 4f core levels, respectively. T_{Au}/T_S is the energy analyzer transmission function, N_{Au} is the bulk atomic density of Au substrate ($5.892 \times 10^{22} \text{ cm}^{-3}$), and L_{Au}^0 is the electron attenuation length for quantitative analysis (1.745 nm) obtained from reference 48. While the sulfur coverage of the monothiol-PEG (MP7M) derived monolayer was calculated to be 4.4×10^{14} of sulfur atoms/cm², those of dithiol-PEGs were 5.8×10^{14} and 5.2×10^{14} atoms/cm² for BP7M and DP7M, respectively (Table 1). In contrast to the monothiol-PEG or dithiol-PEGs, n_s of the disulfide-PEG derived monolayer (6.8×10^{14} sulfur atoms/cm²) was even higher. The SAM of MUA was also prepared as control and its coverage was 6.7×10^{14} atoms/cm². The sulfur coverage in our experiment was higher than that in a previous report, in which the sulfur coverage for a complete alkanethiol on Au estimated by experiment and theory was $5.0 \times 10^{14} \text{ cm}^{-2}$ and $4.6 \times 10^{14} \text{ cm}^{-2}$, respectively.⁶⁰ This comparison suggests that the thiol-coverage obtained from our experiment could be slightly an overestimate. Nevertheless, the relative thiol-coverage is still valid for comparison purpose. First, when we consider the number of sulfur atoms per ligand, the monothiol-PEG (MP7M) is expected to have the largest number

of “PEG” ligands on the Au surface ($4.4 \times 10^{14} / \text{cm}^2$) because of the 1:1 ratio of PEG:S for the monothiol-PEG and 1:2 ratio of PEG:S for the dithiol or disulfide-PEG ($2.6 \sim 3.4 \times 10^{14} / \text{cm}^2$). Even with the larger number of PEG ligands on the Au surface, the monothiol-PEG showed weaker colloidal stability in the previous NaCl and DTT tests because only one thiol anchoring group keeps the PEG ligand from dissociating from the Au surface. Second, considering the structural differences between bidentate PEG, two sulfur atoms of the disulfide unit in TP7M could have a higher chance to bind closely together than two sulfur atoms of less structurally constrained dithiols in BP7M and DP7M. A similar result was reported in the spectroscopic study of Au-S bond formation in monolayers derived from a dithiol monomer and related disulfide-containing polyamides.⁶¹ In that report, the disulfide-containing polymer was attached to the Au surface through both sulfur atoms of the monomer unit to form the anticipated surface-attached loop. In contrast, the dithiol monomer was adsorbed mostly through a single thiol end; another thiol end was unbound. The XPS results can be correlated with the colloidal stability (as determined using NaCl and DTT tests) in two important points; (i) the strong binding of multidentate ligand to the NPs contributed to colloidal stability more dominantly than the total PEG ligand number on NPs, (ii) the structural constraint of two sulfur atoms of the bidentate ligands led to better sulfur atom coverage on the NP surface, which directly reflected the higher colloidal stability.

3.4. Molecular modeling of ligand structures and ligand-gold interactions

To better understand the interactions between the sulfur atoms and the gold surface, we modeled the distances between sulfur atoms in dithiol-PEG (BP7M, DP7M) and disulfide-PEG (TP7M) using UCSF Chimera (version 1.4.1).⁵³ A summary of the S-S and Au-Au distances for each ligand was given in Table 2 and the relative conformations of each anchoring group on the Au surface were pictured in Figure 6b. For this, we chose the lowest energy conformer presenting a geometric compatible with both sulfur atoms of each ligand interacting with a flat gold surface. If the lowest energy conformer did not fit this condition, the other low energy conformers were examined and reported in the Table 2. The simulated distance of two sulfur atoms in each single ligand (S-S distance) was 5.84 Å for BP7M and 4.35 (R isomer) - 4.92 (S isomer) Å of DP7M. In the case of disulfide-PEG in TP7M, the S-S distance was 2.03 Å, which is the shortest among the bidentate ligands studied here. This means that TP7M has more of a structural constraint in

its anchoring group than the two other bidentate ligands, DP7M and BP7M. In order to simplify the further analysis, the structures of DHLA and TA without PEG were also examined, see Figure S2 and S3. In the case of DHLA and TA, the S-S distance in each ligand was 4.22 (*R* isomer) - 4.92 (*S* isomer) and 2.02 Å, respectively, which shows a trend similar to the structures of the same anchoring groups with PEGs, DP7M and TP7M. The positions of the protons attached to the sulfur atoms were changed to place the lone pairs in a position where the interaction with the Au surface was likely to be maximized. This rotation is not required for TA, but the positions of the lone pairs are fixed such that an optimal interaction may require a tilt of the whole molecule relative to the surface. The possible low energy conformers of these two ligands are shown in Figure S4, and their relative positions on Au surface are pictured in Figure 7a. Within all the sulfur-based bidentate ligands, the Au-S interaction is most likely preferred on a pair of gold atoms (Au-Au) separated by either 4.08 Å or 2.88 Å (Table 2, blue circles and red circles in Figure 7b, respectively). In the case of dithiol in DHLA, cleavage of the sulfur-sulfur bond results in structural relaxation, which easily accommodates the Au-Au distance, either two threefold hollow sites (the empty sites in the center between three neighboring Au atoms, Figure 7b, Blue filled circles) or two bridge sites (the middle sites between two neighboring Au atoms, Figure 7b, Blue open circles) on hexagonal close packed Au fcc (111) surface.^{17, 62} In the case of the disulfide in TA, we can suggest an optimal fit when the two S head groups occupy asymmetric bonding sites on the Au surface, with one S located approximately in the Au hollow site and the other S located near the adjacent Au bridge site (Figure 7b, Red filled circles) because the S-S bond distance of TA (2.02 Å) does not match the distance between the hollow sites of Au(111) (1.7 or 2.9 Å).^{62, 63} This free-ligand modeling simply demonstrates that the constrained disulfide ligand (TA or TP7M) could have a greater chance to pack more densely on the Au surface than the flexible dithiol ligands because of the closer S-S distance compared to the other ligands. The modeling studies discussed here are consistent with the experimental results. The structurally constrained disulfide ligand showed the higher sulfur coverage on Au surface and higher colloidal stability on the AuNPs than the flexible dithiol ligands despite the fact that the Au surface and AuNP have different curvature and slightly different Au lattice structure.

Conclusion

Here, we studied how the structures of anchoring groups of surface ligands affect the colloidal stability of AuNPs using a series of PEG-based modular ligands appended with four different sulfur-based anchoring groups (monothiol, flexible dithiol, constrained dithiol and disulfide). The PEG-coated AuNPs were prepared by ligand exchange of citrate-stabilized AuNPs with each ligand. The colloidal stability of the AuNPs in harsh environmental conditions was monitored visually and spectroscopically. The AuNPs coated with dithiol- or disulfide-PEG exhibited much better stability under high salt concentration (2M NaCl at 100 °C) and against ligand replacement competition with DTT (1.5 M) than those coated with their monodentate counterpart. Furthermore, XPS analysis revealed that the disulfide-PEG ligand had the highest Au-S ratio on the Au surface, indicating the highest surface coverage among them. This implies the ligands with structurally constrained dithiol or disulfide showed better colloidal stability and higher sulfur coverage on the Au surface compared to the ligands with more flexible dithiol and monothiol. The XPS data were also supported by structural modeling studies of the ligands: structurally constrained disulfide ligand showed the smallest S-S distance and such a compact bidentate structure could have a higher chance of dense packing on the Au surface. The present study indicates that the colloidal stability of NPs can be significantly enhanced by (i) a multidentate chelating effect and (ii) use of a constrained and compact structure within the anchoring groups. These aspects would certainly help us design more sophisticated surface ligand structures and enhance the colloidal stability of NPs, which is a crucial parameter for a variety of biological applications.

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Supporting Information Available. The synthesis of ligand, hydrodynamic size of AuNP-ligands, molecular modeling were included in the supporting information. This information is available free of charge via the Internet at <http://pubs.acs.org>.

Table 1. Relative sulfur coverage of each ligand on Au surface analyzed by XPS. The surface coverage of S atoms was calculated using S 2p and Au 4f (substrate) intensities as described.

	MP7M	BP7M	DP7M	TP7M
Sulfur Coverage ($\times 10^{14}$ atoms/cm ²)	4.4 $\pm$ 0.16	5.8 $\pm$ 0.30	5.2 $\pm$ 0.56	6.8 $\pm$ 0.85

Table 2. Distances (Å) in gold-sulfur complexes for each ligand.

Compound	S-Au	S-S	Au-Au ^c
MP7M	2.29	NA	NA
BP7M	2.35, 2.30	5.84 $\pm$ 1.35 ^a	4.08
DP7M	2.35, 2.31	4.35 (<i>R</i>), 4.92 (<i>S</i>) ^b	4.08
TP7M	2.45, 2.30	2.03	2.88
DHLA	2.32, 2.29	4.22 (<i>R</i>), 4.92 (<i>S</i>) ^b	4.08
TA	2.27, 2.27	2.02	2.88

^a The average value of multiple conformations in the case of BP7M is presented here, because there are primarily two dihedrals having two minima giving multiple conformations are within a few kcal.

^b *R* and *S* indicate the enantiomers of DP7M and DHLA since DHLA (dihydrolipoic acid or 6,8-dimercaptooctanoic acid) has a chiral center at C6 position. Those two enantiomers have slightly different low energy conformer for both sulfur atoms interacting with a flat gold surface.

^c The corresponding Au-Au separation with each ligand docking on the Au surface in the energy minimization model (Blue circles and Red circles, respectively in Figure 7b)

Figure Caption

Figure 1. (a) Chemical structures of the series of PEG ligands with different sulfur-based anchoring groups: MP7M, BP7M, DP7M, TP7M. (b) The absorption spectra of AuNPs before (AuNP-citrate) and after ligand exchange with the PEG ligands: AuNP-MP7M (Red), AuNP-BP7M (Orange), AuNP-DP7M (Green) and AuNP-TP7M (Blue). (c) Dynamic light scattering (DLS) data of AuNPs before (AuNP-citrate) and after ligand exchange with the PEG ligands: AuNP-MP7M (Red), AuNP-BP7M (Orange), AuNP-DP7M (Green) and AuNP-TP7M (Blue) were the data of 2 year-old sample after ligand exchange. AuNP-TP7M (Blue dotted line) is measured just after ligand exchange as a fresh sample control.

Figure 2. Side-by-side comparisons of the dispersion stability of AuNPs with different ligands (marked at the bottom of pictures as MP7M, BP7M, DP7M and TP7M). The images of freshly prepared AuNP-TP7M (Control) were also shown in parallel to see the sample color changes during the experiments. (a) NaCl and heat resistance test: colloidal AuNPs in 2M NaCl after 0, 5 and 15 minutes at 100 °C (the first three pictures). Heat resistance test: colloidal AuNPs after heating (100 °C) in 2M NaCl during 15 minutes followed by 24 hours at room temperature (the last picture). (b) DTT resistance test: colloidal AuNPs in 1.5 M DTT, 0.8 M NaCl and 10 mM NaOH after 1, 4, 20, 60 and 90 minutes at room temperature.

Figure 3. UV-vis absorption spectra of 15 nm AuNP dispersions before (solid line) and after (dotted line) heating in 2 M NaCl aqueous solution for 15 min: (a) MP7M-AuNPs; (b) BP7M-AuNPs; (c) DP7M-AuNPs; (d) TP7M-AuNPs.

Figure 4. Time course measurements of the UV-vis absorption spectra of 15 nm AuNP dispersions with 1.5 M DTT, 0.8 M NaCl and 10 mM NaOH in water: (a) MP7M-AuNPs; (b) BP7M-AuNPs; (c) DP7M-AuNPs; (d) TP7M-AuNPs in 0.2, 0.3, 0.5, 1, 2, 3 minutes, and every 2 minutes from 4 to 20 minutes; the surface plasmon bands shift from left to right.

Figure 5. (a) The concept of the accumulated flocculation of AuNP-PEGs using UV-vis absorption spectrum based on equation (1). (b) The accumulated flocculation (AF) of 15 nm AuNP under heat resistance test. (c) The changes of the accumulated flocculation (AF) of 15 nm

AuNP during DTT resistance test. The error was less than 10% based on our absorption measurements. (d) The shifts of SPB (surface plasmon band) of AuNPs during DTT resistance test: MP7M-AuNPs (diamond), BP7M-AuNPs (triangle), DP7M-AuNPs (square) and TP7M-AuNPs (circle). DTT solution: 1.5 M DTT, 0.8 M NaCl and 10 mM NaOH in water.

Figure 6. (a) S 2p core line spectra fitted to one or two Voigt doublet(s) (solid line) and superimposed on a polynomial background function (dashed line). Spin-orbit intensity ratio of the S 2p_{1/2} and 2p_{3/2} components was set to 0.5, and the spin-orbit splitting was kept at 1.2 eV. The binding energy of the bound S 2p_{3/2} component was found to be 162 ± 0.1 eV. The spectral intensity of the bound S 2p doublet is indicated by colored shading. (b) Simulated possible conformation of anchoring group of each ligand on the Au surface: MP7M (left up); BP7M (right up); DP7M (left bottom); TP7M (right bottom).

Figure 7. (a) Modeled possible conformation of DHLA (Left) and TA (right) on the Au surface. (b) DHLA can interact with a pair of gold atoms positioned at two Au threefold hollow sites (Blue filled circles) or two Au bridge sites (Blue open circles), while TA can interact with a pair of atoms positioned at Au threefold hollow site and Au bridge site (Red filled circles).

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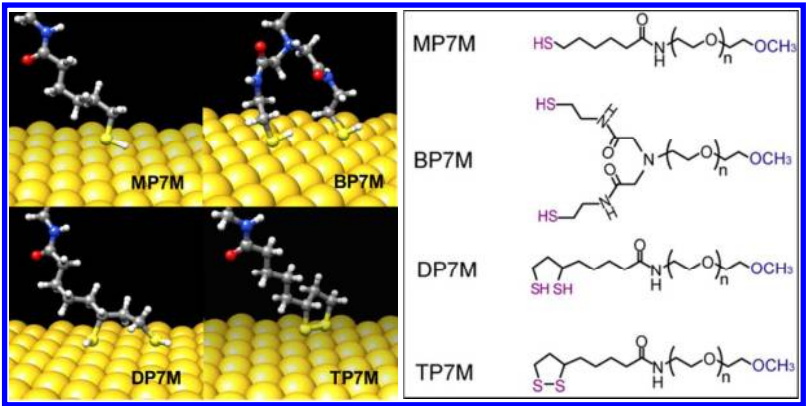
Table of contents entry

Colloidal Stability of Gold Nanoparticles Coated with Multithiol-Poly(ethylene glycol) Ligands: Importance of Structural Constraints of the Sulfur Anchoring Groups

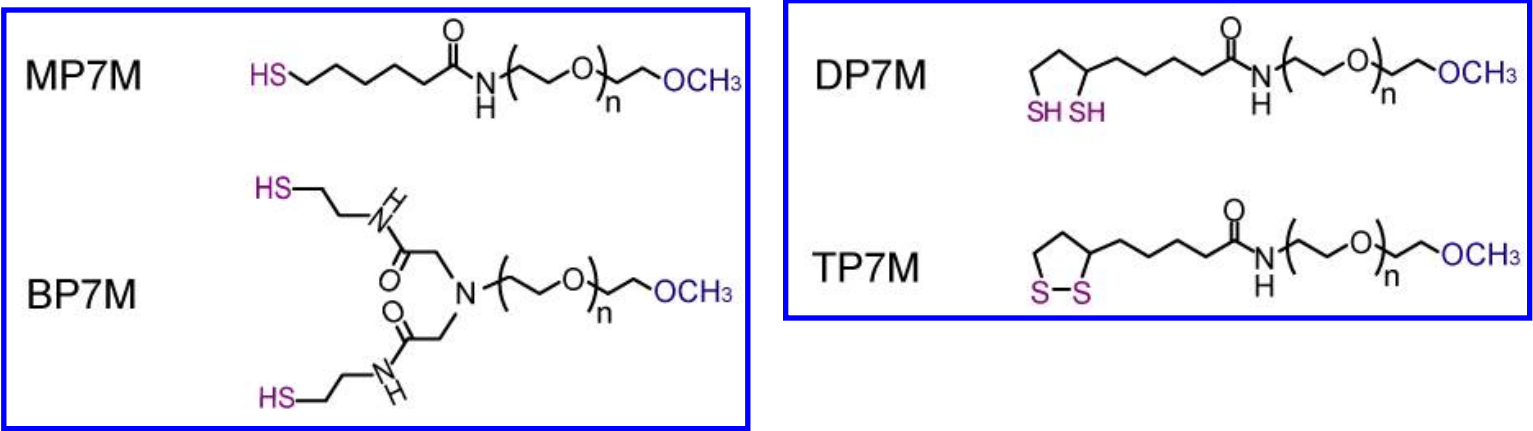
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Eunkeu Oh, Kimihiro Susumu, Antti J. Mäkinen, Jeffrey R. Deschamps, Alan L. Huston and Igor L. Medintz

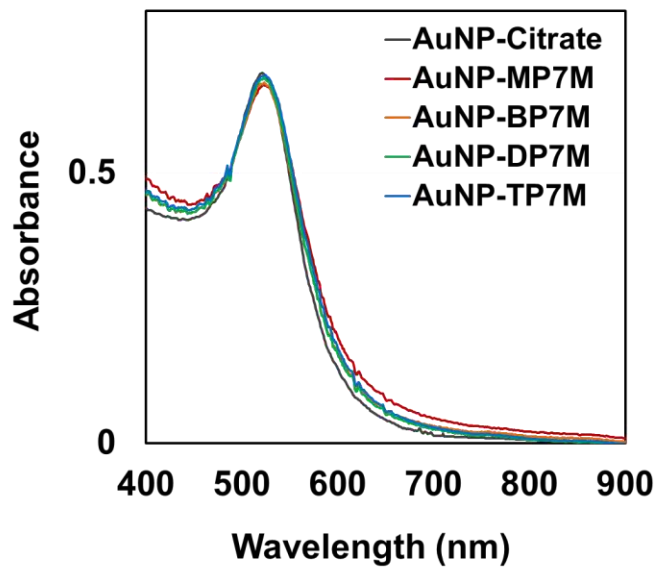
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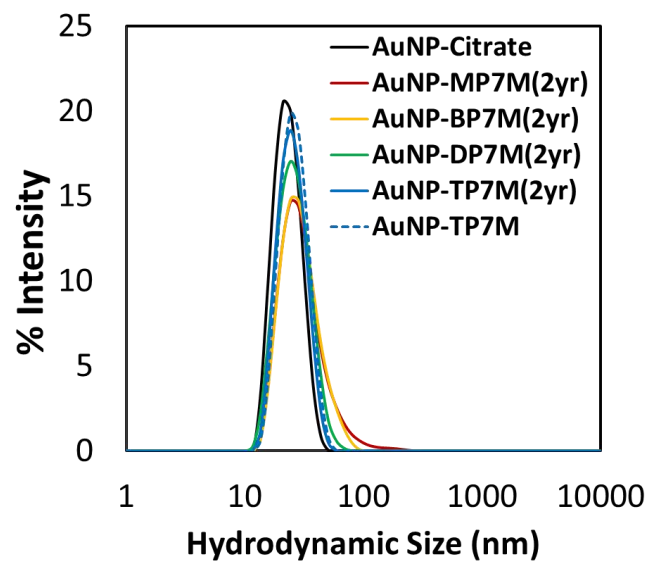
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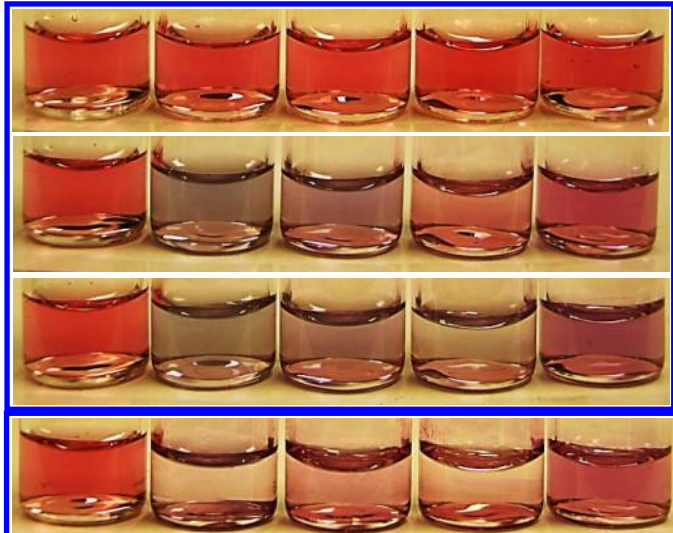
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(a)

2 M NaCl at 100°C



0 min
5 min
15 min
15 min at 100°C
+ 24 hr at RT

Cont. MP7M BP7M DP7M TP7M

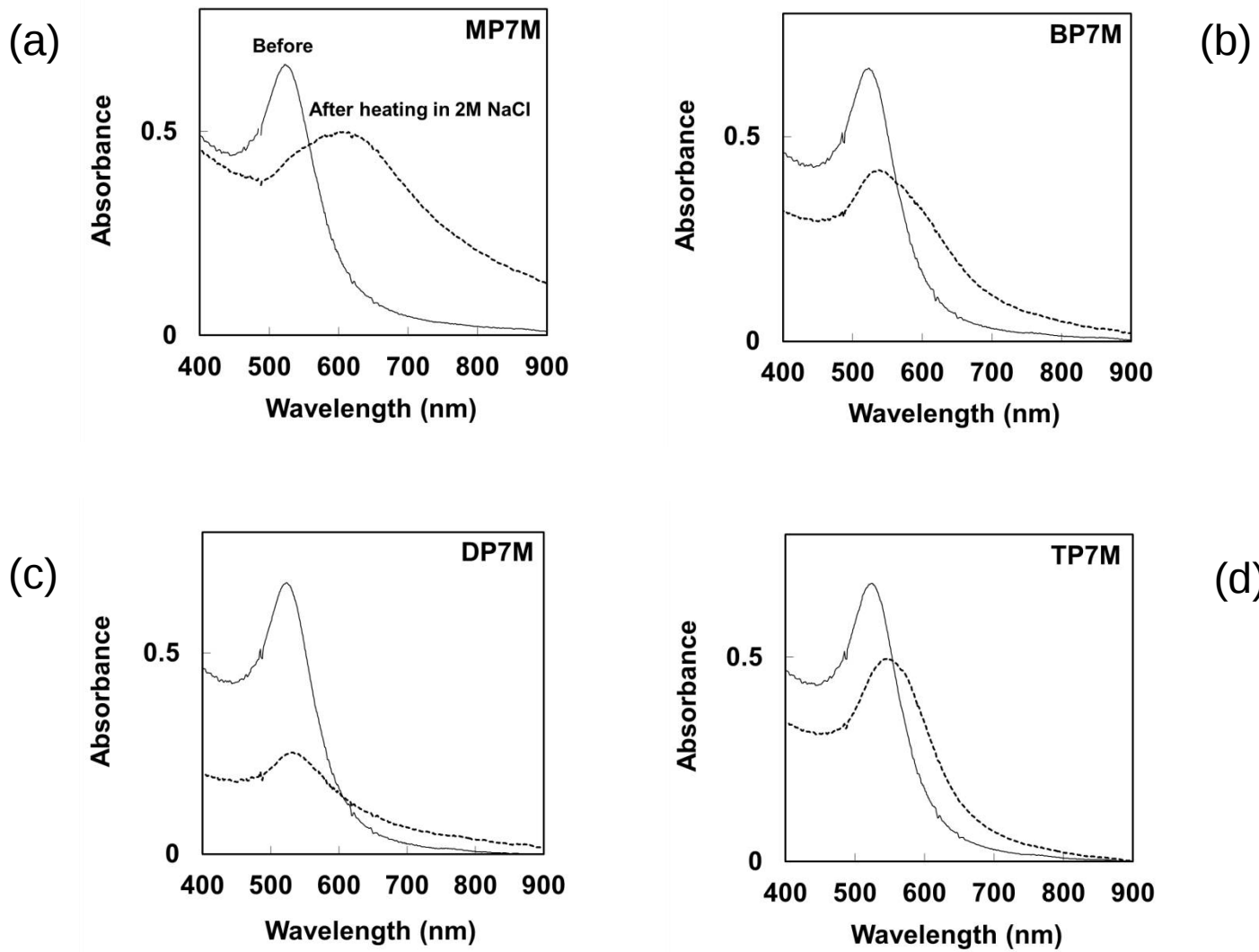
(b)

1.5 M DTT, 0.8 M NaCl, 10 mM NaOH

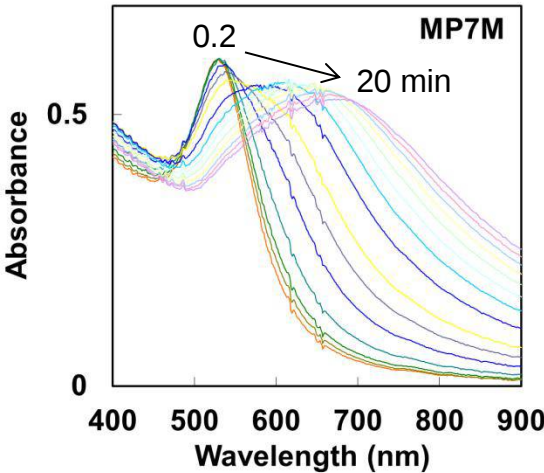


1 min
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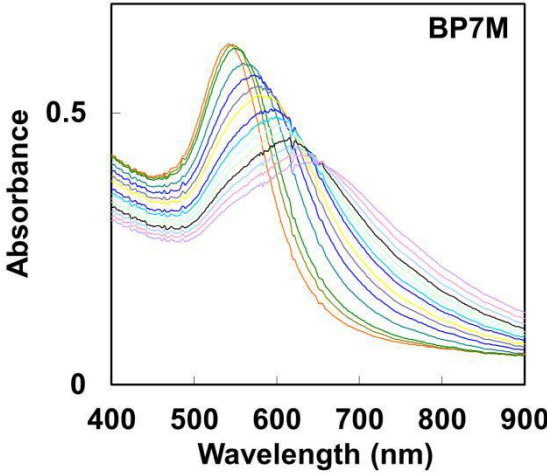
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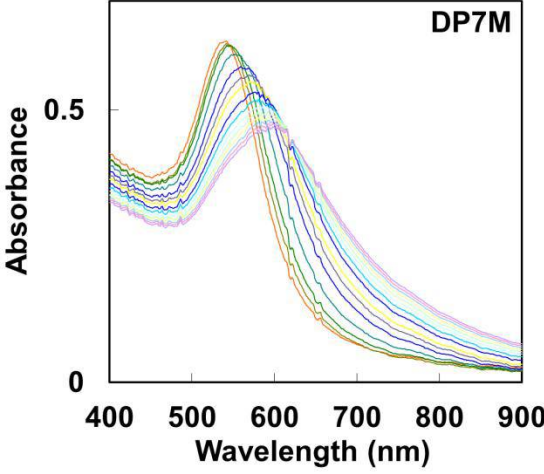
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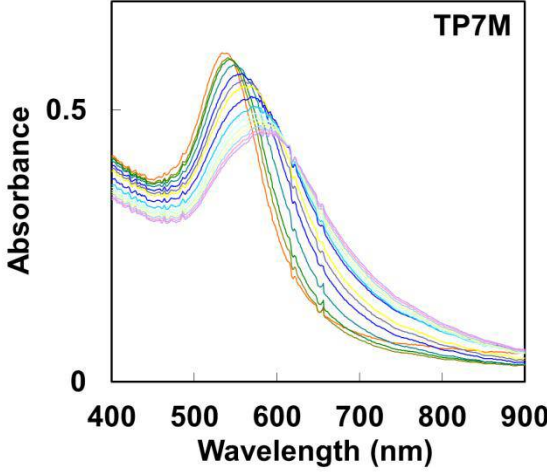
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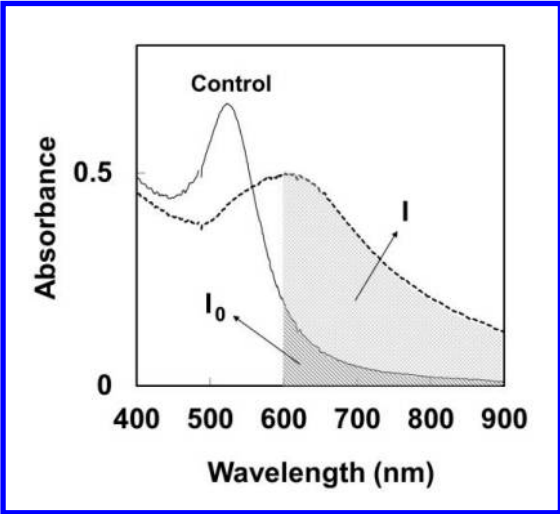
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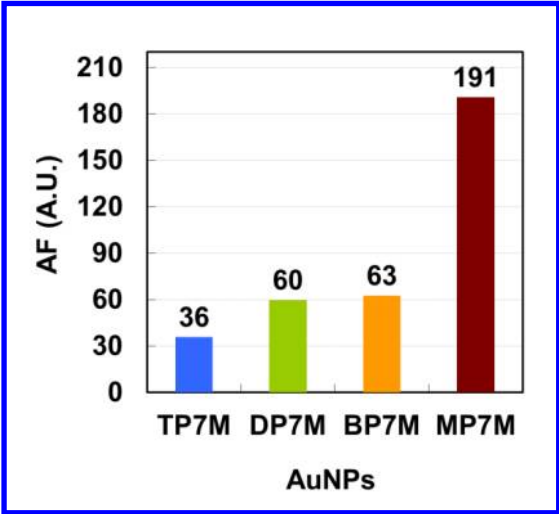
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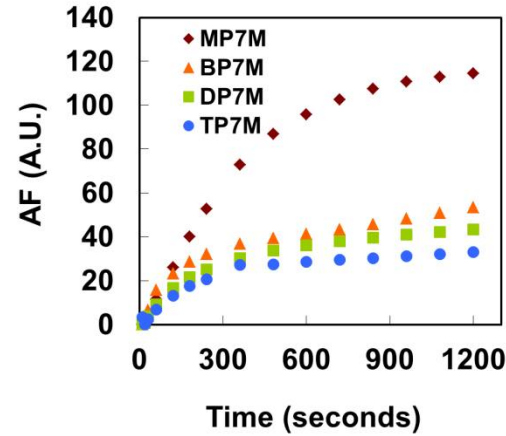
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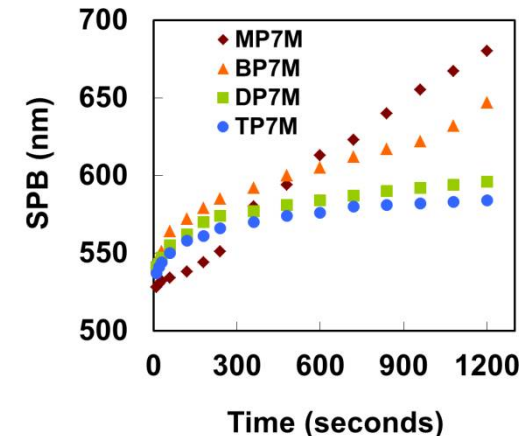
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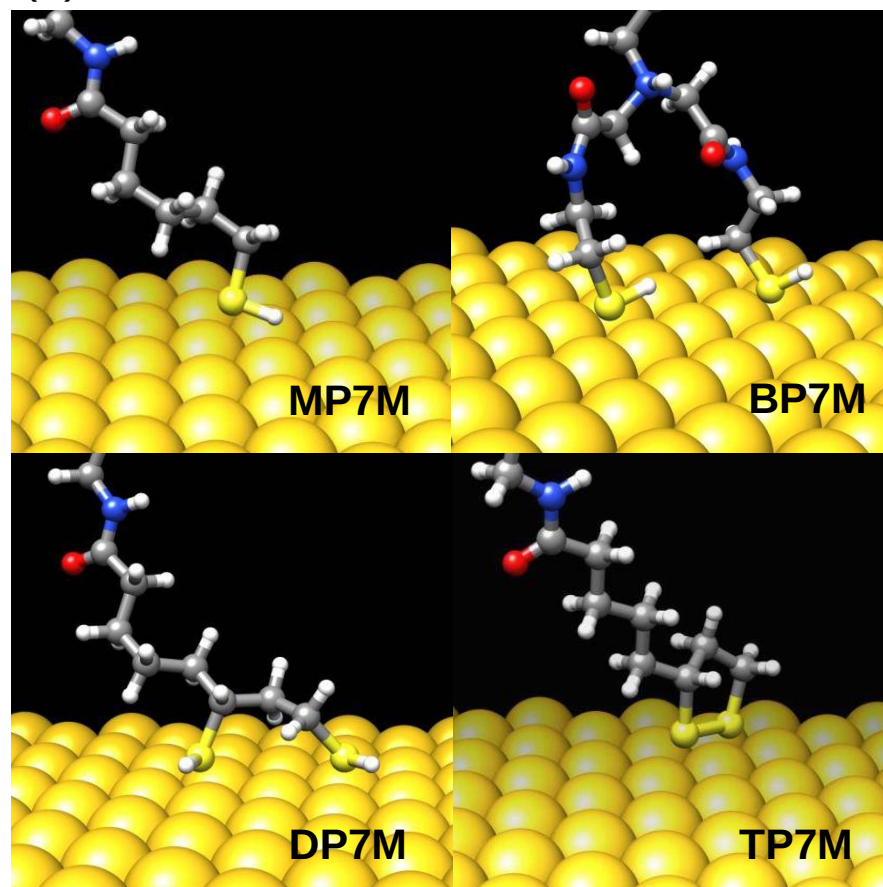
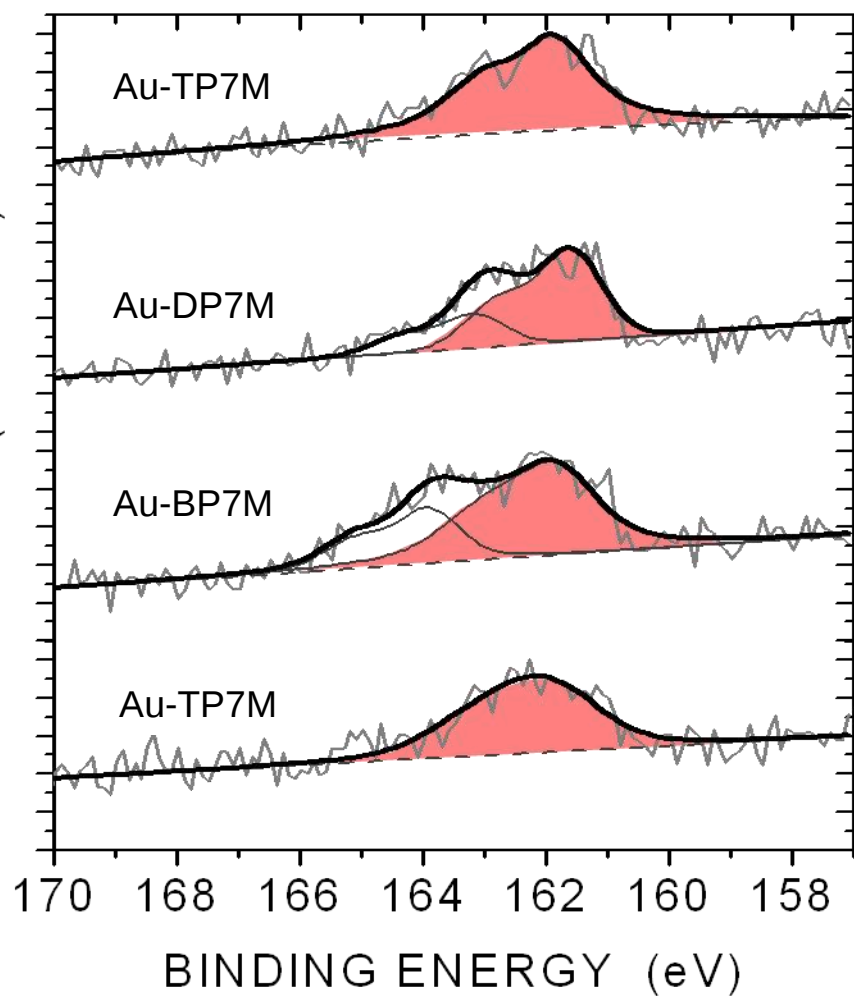


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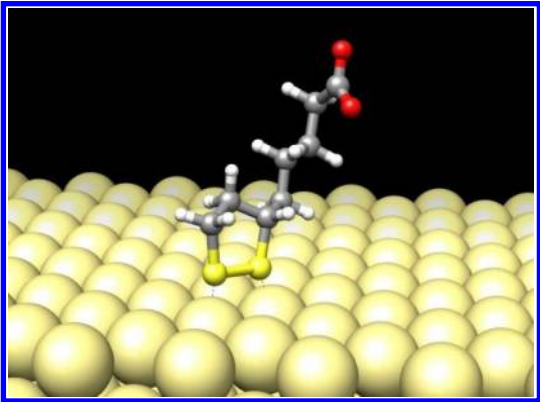
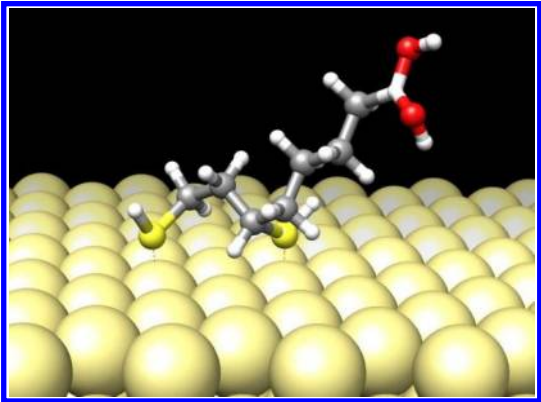




(a)

DHLA

TA



(b)

